

Monitoring The Evolution of SNR 1987A With *Chandra*

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Abstract. We report on the results of our monitoring program of SNR 1987A with the *Chandra X-Ray Observatory*. The high resolution images and the spectra from the latest *Chandra* data suggest that the blast wave has reached the dense inner ring in the western side of the SNR, as well as in the east. The observed soft X-ray flux is increasing more rapidly than ever, and the latest flux is four times brighter than three years ago.

1. Introduction

We continue our monitoring program of SNR 1987A with the Advanced CCD Imaging Spectrometer (ACIS) on board the *Chandra X-Ray Observatory*. As of 2002 December, we have performed a total of seven observations (Table 1). Results from the first six observations have been reported in the literature (Burrows et al. 2000; Park et al. 2002, 2003; Michael et al. 2002). The X-ray morphology was ring-like and asymmetric (brighter in the east) with the emergence of X-ray-bright spots. The X-ray spectrum was described with a plane-parallel shock in a non-equilibrium ionization (NEI) state with an electron temperature of $kT \sim 2.5$ keV. A blast wave shock velocity of $v \sim 3500$ km s⁻¹ was derived from the detected X-ray line profiles, which also provided direct evidence of an electron-ion non-equilibrium behind the shock. The X-ray flux was non-linearly increasing as the blast wave approaches the dense inner ring. We here report on the results from the latest *Chandra* observations of SNR 1987A.

2. Morphology

The ACIS images (Fig. 1) have been generated by the data reduction process described in Burrows et al. (2000) and Park et al. (2002). Fig. 1 shows the overall brightening and development of new X-ray bright spots, particularly in the western side of the SNR. SNR 1987A is expected to be a complete ring in

Table 1. <i>Chandra</i> /ACIS Observations of SNR 1987A			
ObsID	Date (Age ^a)	Exposure (ks)	Source counts
124+1387 ^b	1999-10-06 (4609)	116	690
122	2000-01-17 (4711)	9	607
1967	2000-12-07 (5038)	99	9031
1044	2001-04-25 (5176)	18	1800
2831	2001-12-12 (5407)	49	6226
2832	2002-05-15 (5561)	44	6429
3829	2002-12-31 (5791)	49	9274

^a Day since the SN explosion.

^b The first observation was split into two sequences, which were combined in the analysis. The ACIS-S3+HETG was used. The ACIS-S3 was chosen for the other observations.

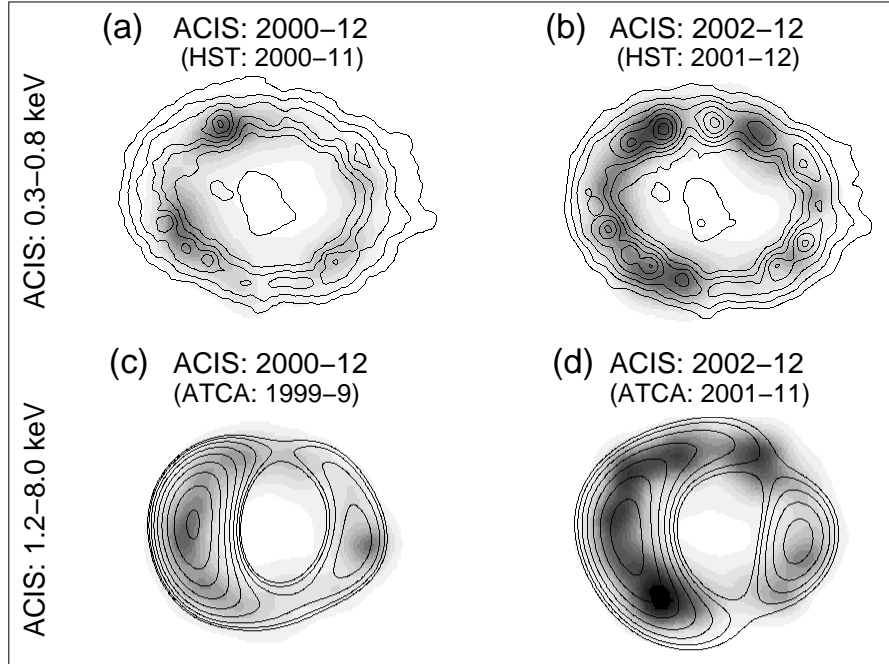


Figure 1. The exposure-corrected ACIS images of SNR 1987A. Darker gray-scales are higher intensities. The image deconvolution and smoothing, after performing a sub-pixel resolution, have been applied. Top panels (a, b) are the 0.3–0.8 keV, and bottom panels (c, d) are the 1.2–8.0 keV band images. The optical and the radio contours are overlaid.

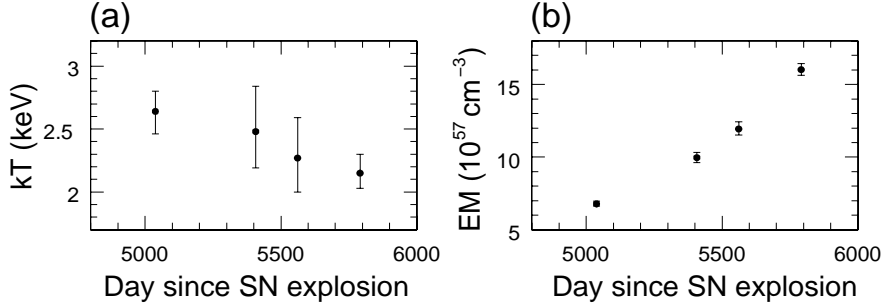


Figure 2. The electron temperature and the emission measure variations of SNR 1987A between 2000-12 and 2002-12.

X-rays. In 2000, the strong correlation between the soft X-ray and the optical images was interpreted as emission from the slow shock encountering protrusions of the dense inner ring. The correlation between the hard X-ray and the radio images was consistent with emission from the fast shock propagating into an HII region interior to the ring. As of 2002-12, correlations between the X-ray and the optical/radio images are more complex than such a simple picture, which is perhaps expected as the blast wave is reaching the main body of the inner ring.

3. Spectrum and Flux

The X-ray spectrum from each observation can be fitted with a single NEI plane shock model with an electron temperature of $kT \sim 2\text{--}3$ keV and low abundances (0.1–0.5 solar). Based on the data with the most significant photon statistics, we find that the electron temperature has decreased slightly, while the volume emission measure (EM) has substantially increased for the last two years (Fig. 2). These results are consistent with our physical picture of the blast wave encountering a dense circumstellar medium (CSM). A growing contribution to the observed spectrum from the slow shock is then expected (Michael et al. 2002). A two-temperature model indeed statistically improves the fit, particularly with the latest data (Fig. 3). The soft component ($kT \sim 0.25$ keV) implies a slow shock velocity ($v \sim 400 \text{ km s}^{-1}$) with a highly advanced ionization state ($n_e t \sim 10^{13} \text{ cm}^{-3} \text{ s}$). This is consistent with the decelerated shock front in the dense CSM. The 0.5–5 keV band flux from the soft component has tripled since 2000-12, while the flux from the hard component has doubled. We note that the flux increase from the slow shock in the western half (by a factor of 6) is much larger than in the east ($\sim 30\%$). The flux increase from the fast shock is constant between the east and the west. These results suggest that the blast wave has now begun to encounter the dense CSM in the western side of the SNR a few years after it did in the eastern side. The X-ray lightcurve shows a non-linear flux increase rate (Fig. 4). We have thus attempted non-linear fits to the data: e.g., in Fig. 4, we present a fit by assuming an exponential density distribution along the radius of the inner ring. The best-fit model implies an ~ 20 times higher density in the inner ring than in the HII region. The actual density contrast, which might be higher than this, could be measured as the shock-CSM interaction proceeds.

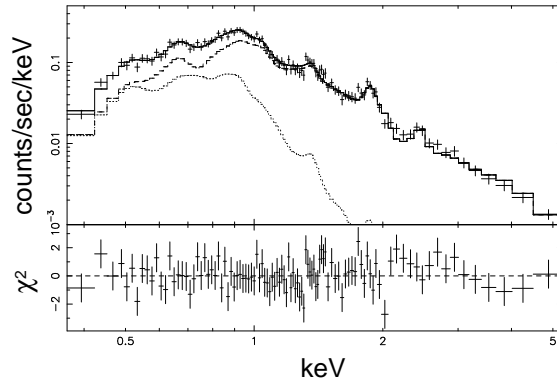


Figure 3. The X-ray spectrum of SNR 1987A as of 2002-12. The best-fit two-component plane shock model is overlaid.

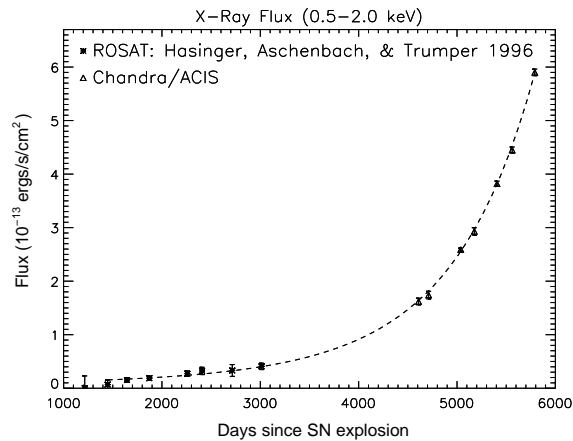


Figure 4. The X-ray lightcurve of SNR 1987A. The dashed curve is a best-fit model assuming an exponential distribution of the radial density profile interior to the inner ring.

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